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SPHERICAL DRIVE-IN TARGET

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AN INTENSE 14 MeV NEUTRON SOURCE USING A SPHERICAL DRIVE-IN TARGET*

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ABSTRACT

A 14 MeV neutron radiation test facility using a drive-in spherical-shell target is discussed. This concept is based on a modest extrapolation of the present ion source technology and the drive-in target principle. Beams of equally mixed deuterons and tritons from four ion sources are driven into a spherical target (diameter ≈ 20 cm) from all directions. The inside of the spherical shell is accessible through two ducts for neutron irradiation samples, providing a large irradiation space with no significant variation in neutron flux densities. The expected neutron source intensity at the shell is $S \approx 2 \times 10^{12}$ n/cm² sec for a 300 keV — 15 mA/cm², D-T mixed beam on a titanium target. The neutron flux obtained inside the shell increases monotonically with the radial distance from the minimum $\phi = S$ at $r = 0$ to, for instance, $\phi = 1.65 S$ at $r = 0.9 a$, where a is the radius of the spherical shell. This facility has a unique advantage in that a number of irradiation experiments can be performed simultaneously and a fairly uniform neutron flux can be obtained over a irradiation sample of large size. The target is designed to handle 4-5 kW/cm² of beam power by utilizing a "shell" of vortex-flow generators. D-T mixed gas is continuously recirculated and the target plating is done in-situ. Preliminary design ideas will be discussed.

INTRODUCTION

Interest in intense high energy neutron sources has recently been increased substantially by the demand from two different applications, i.e. material testing and damage studies for controlled nuclear fusion reactors and neutron radiotherapy. Neutron source requirements for the CTR materials program were summarized by Persiani[1]. In general, neutron fluxes at the sample location of at least 10^{12} n/cm² sec with the D-T neutron spectrum seem to be needed. In the long run, however, a neutron source is desired which produces

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neutron fluxes comparable to the expected wall fluxes in fusion reactors ($\approx 10^{14}$ to 10^{15} n/cm² sec) and neutron fluences corresponding to a few years of reactor operation. ✓

There are at present several accelerator-target systems either existing or proposed which utilize D-T reaction on such targets as tritium-loaded titanium target, D-T mixed beam drive-in target, and gas target. The LLL rotating target system produced a source intensity of 5×10^{12} n/sec from a "fresh" 1.5 cm² source spot using a 350 keV - 22 mA D⁺ beam[2]. Accessibility to the source spot is within ≈ 5 mm. However, the neutron yield decreases with the beam time, the target lifetime being about ≈ 700 mA-hrs. Kim, Hilton and Hendry[3] reported that they obtained 6×10^{12} n/sec from 5.5 cm diameter source spot with D-T mixed beams of 170 keV and 0.3 A on chromium target. Access to their source plane is limited to about 10 cm since the target at high negative potential should be separated by the HV vacuum gap from the ground. The proposed LASL source[4] using a supersonic gas jet target aims for a total neutron yield of $\approx 8 \times 10^{14}$ n/sec at 300 keV and 1A/cm². It is, however, far beyond the present steady state ion beam technology to obtain 1 A tritium ion beam on a 1 cm² spot at a distance of a few meters from the ion source and to remove the power on a steady state basis. Accessibility would be another serious problem with this machine.

In this paper we propose a neutron irradiation facility using a drive-in spherical-shell target, which will overcome some of the disadvantages of the other systems mentioned above. In the proposed concept, a large irradiation volume is available with the neutron flux greater than 2×10^{12} n/cm² sec and the total neutron yield of 2×10^{15} n/sec, and thus the accessibility is no longer a problem. The design of ion sources and target is based on direct and modest extrapolation of the existing technology, and therefore there is a greater possibility of success within a minimal amount of time and cost. Long, reliable operation with no degradation in source intensity will be possible due to the drive-in feature and the in-situ target plating. We will present the preliminary conceptual design ideas on critical components such as ion source, target construction and plating, gas recirculation and pumping, and estimated neutron intensities.

ION BEAM TECHNOLOGY CONSIDERATIONS

During the past 20 years, hydrogen ion source and beam technology has advanced enormously with the primary effort resulting from the CTR applications of neutral beam injection into plasma devices. These sources[5] at present are typically capable of producing current densities of $\approx 0.3 - 0.5$ A/cm² over tens of cm² with extracting electric fields of ≈ 100 kV/cm at total energies of 15-40 keV in pulsed modes of operation. The duoplasmatron ion sources[6] developed for DCX-2 injectors have been extensively operated under steady state conditions at energies of 100-600 keV and ion currents of 0.3 - 0.5 A.

Results from all these ion sources showed that extracted current densities are limited by the Child-Langmuir current, i.e., $j = 5.44 \times 10^{-8} A^{-1/2} V^{3/2} z^{-2}$ where j is the current density extractable in Amp/cm², A the atomic mass number of extracted ions, V the extraction potential in volts and z the gap distance in cm. The breakdown voltage in the gap on the other hand goes roughly as $V \propto z^{1/2}$, and thus the current density scales as $j \propto V^{-5/2}$.

Without any external focusing, these beams have typically e-folding angles of $\pm 1^\circ$. The available current densities at a target some distance away from an extraction plane will, therefore, be limited by these factors, namely (a) the limitation on the extracted current; (b) the intrinsic divergence of beams, and (c) non-delta-function distribution of beam current density.

Taking an example in which 1 A of beam is desired on a 1 cm diameter spot at a distance of 1 m from a source, assume a gaussian current distribution with a divergence of $\pm 1^\circ$ e-folding angle. Then, a total beam current of 10 A is needed from the source in order to supply 1 A on the target spot, which implies the anticipated degree of difficulty in both the ion extraction and handling of the waste power. It is therefore apparent that extra focusing fields are needed for the case in which high current densities are desired on a target.

In our conceptual design, the beam current densities are in the vicinity of 15 mA/cm² and the total beam current output from a single ion source is about 4 A at 300 keV. The extraction region will be a direct adaptation of the present ORMAK injector[7] and several accelerating stages can be added to make up 300 keV. Thermal loading on ion source components and electrodes would be the main difficulty in obtaining steady state beams. However, the anticipated current density is about a factor of ten lower than the ORMAK injector, and thus the required arc current and the power loading on the extraction electrodes should be reduced to a level satisfactory for dc operation. One important feature of the multiaperture source is the ability to steer the individual beamlets by aperture displacement[8]. Since the target spot is a section of a sphere, it will be desired to steer beamlets by this technique so as to yield a uniform current density over the entire spherical target.

MECHANICAL DESIGN

The spherical target is suspended inside a spherical vacuum vessel as sketched in Fig. 1. All the ion sources and the vacuum pumps are directly coupled to the spherical vessel. Ion beams from four ion sources on the same horizontal plane will provide approximately uniform irradiation on the entire sphere except the two supporting ducts at opposite poles. The diameter of the spherical target is about 20 cm and the size of the vacuum vessel is to be determined by the required access area for the pumps.

Total gas loading of $\sim 6 \text{ TL/sec}$ is estimated. The D-T mixed gas is recirculated in a completely closed loop system by employing a number of reversible getter pumps with both inlet and outlet valves operated in synchronization with the pump heaters. For example, consider a SAES getter pump, GP 500W. It has a pumping speed of 1400 liters/second at about 350°C for hydrogen gas. The hydrogen gas can be recovered by further heating the getter up to 700°C. For the estimated gas loading, we would need fifty such pumps. Each pump or each group of pumps is to be used in succession for gas recovery and recirculation while the rest are performing the pumping. In this way the gas recovery is made in continuous fashion without causing any perturbation on the machine operation. A simplified flow circuit is shown in Fig. 2. In addition to the getter pumps, there is employed a mercury diffusion pump with a molecular pump functioning only when roughing out the vessel. A tritium removal system ensures the exhaust gas free of tritium contamination before

removal system ensures the exhaust gas free of tritium contamination before the occasional release of air or helium from the facility.

DRIVE-IN TARGET DESIGN CONSIDERATION

It is a relatively old idea to produce fusion neutrons by constantly bombarding a metal drive-in target with deuterons or mixed deuterons and tritons. It is desired that the target would hold as many deuterons (or tritons) as possible for the incoming particles to react with. Assuming that the hydrogen concentration in a target is constant across the stopping range[9], we obtain an expression for the neutron source intensity per unit irradiated area of target surface,

$$S = \frac{jC}{e} \int_0^R \sigma[E(x)] dx \quad (1)$$

where j is the current density, C the saturation concentration of hydrogen, σ the fusion reaction cross section, R the stopping range of incoming particles in a target, e the electronic charge, and $E(x)$ the energy of the incoming particle as a function of penetration depth. For solid target C is 10^{22} to 10^{23} cm^{-3} while the range is only on the order of several microns for a few hundred keV ions. Most of the particle energy is lost to the metal atoms.

The choice of drive-in target material is thus concerned with C and R as well as with other physical properties. We are considering titanium, zirconium and yttrium as potential target materials. Some relevant properties of these metals are summarized in Table I. Plating of the chosen material on the target backing will be done in-situ by utilizing ion plating technique with the same ion source. Since the thin coating of target metal will be sputtered away by bombardment of deuterons and tritons, the plated layer must be replenished in order to ensure a long target lifetime. The plating metal can possibly be vaporized, ionized and then extracted at some low voltages in the same ion sources that produce D-T beams. This could be done periodically to maintain a coating layer thin enough for good heat conduction and thick enough to stop all the deuterons and tritons.

The target is formed into the shape of a spherical shell with two opening ducts on opposite poles. These ducts make the mechanical connection and also serve as an annular water channel. Irradiation samples can be inserted through the ducts. The power handling capability of a target is one of the most important factors in obtaining high neutron yields. One approach is to assemble a bundle of tubes on the outside surface of a spherical shell so as to completely cover up the surface and to stop all the incoming particles. These tubes will be plated with chosen target material. All the tubes join to manifolds at the top and bottom duct. Each tube contains full length twisted inconel tape swaged in place, which provides high speed vortex-flow. The power handling capability will be much more enhanced by the swirl flow and by the azimuthal heat conduction. In some ranges of Reynolds number and tape twist ratio, swirl flow produces ratios of heat transfer coefficient to frictional pumping power as much as two-fold larger than straight flow of the

same fluid at the same temperature through the same tube[10]. Burnout heat fluxes tested[10] ranges from 2 to 5 kW/cm² for copper tubes and from 5 to 12 kW/cm² for nickel tubes, depending upon the tube size, the pressure drop, and other parameters. Calculations show that it is possible to design such a tube target capable of handling heat fluxes of 4-5 kW/cm².

NEUTRON SOURCE INTENSITY

The neutron source intensity per unit irradiated area can be estimated by using Eq. (1) with some modification to account for molecular ion components[9]. Considering titanium as the target material with a possible hydrogen concentration of 6×10^{22} cm⁻³ corresponding to one to one ratio, we estimate the neutron source density as a function of accelerating energy in Fig. 3. The neutron source intensity per kW of beam power starts to level off at beam energies above 300 keV. Therefore, 300 keV would be the apparent choice. At 300 keV, we estimate $S \approx 2 \times 10^{12}$ n/cm² sec for a beam power of 4.5 kW/cm². The total neutron yield from the 20 cm diameter spherical target would then be 2.5×10^{15} n/sec.

In order to estimate the neutron flux available inside the target sphere, that is the irradiation space, we will make the following approximations.

- (a) Neutrons are emitted isotropically from the uniform plane source of spherical shell with radius a and source intensity S per unit area per second.
- (b) Neutron attenuation through the target wall will be neglected.

The first approximation is well justified since the emission is almost isotropic at these energies and the perturbation due to the presence of the ducts is only a few percent. Attenuation in the wall is also less than a few percent. Since the geometry is spherically symmetric, the neutron flux density at r is given by

$$\begin{aligned} \phi(r) &= \iint \frac{S a^2 \sin \theta d\theta d\phi}{4\pi[a^2 + r^2 - 2ar \cos \theta]} \\ &= \frac{S}{4(r/a)} \ln \left[\frac{1 + r/a}{1 - r/a} \right]^2 \end{aligned} \quad [2]$$

Two limiting cases check the derivation, i.e., $\phi = S$ as r goes to zero and

$\phi(r) = \frac{a^2}{r^2} S$ as $r/a \gg 1$. Eq. (2) is plotted in Fig. 4, which shows that the flux has its minimum ($\phi = S$) at the center and increases monotonically but slowly with r . For instance, $\phi = 1.65 S$ at $r = 0.9 a$. This fact is the most important merit with the use of spherical target. The spherical shell source of neutrons provides a large useful space for sample irradiation with a small variation in flux densities, and yet the obtainable flux density is at least the neutron source intensity at the source shell.

CONCLUSIONS

We believe that the near-term development of D-T neutron sources with modest flux levels is greatly needed in order to have a large number of material tests made in the earliest possible time. The drive-in spherical target concept presented in this paper is based on the well-established, simple drive-in principle, and has several unique advantages in connection with the sphericity of the neutron source plane. In summary, important merits of the concept are:

- (a) There is a large irradiation space available with little variation in neutron flux density and therefore many irradiation experiments can be made simultaneously.
- (b) The available D-T neutron flux density is at least equal to the source intensity ($\approx 2 \times 10^{12}$ n/cm² sec) and increases with the radial distance.
- (c) The ion source and beam requirements are modest extrapolations from the existing ORMAK neutral beam injectors and can benefit from the injector development programs under way at ORNL.
- (d) Undisturbed, reliable steady state operation can be achieved by the use of in-situ ion plating of the target material.
- (e) It is believed that the facility can be built in a short period of time with modest funding.

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FIGURE CAPTIONS

- Fig. 1. Sketch of Spherical Target Neutron Source.
- Fig. 2. Gas Recirculation Flow Circuit.
- Fig. 3. Neutron Yield Per kW of Beam Power Versus Beam Energy for Titanium Target.
- Fig. 4. Neutron Flux Density Variation as a Function of Radial Distance Inside and Outside the Neutron Source Shell.

TABLE I
Some Target Materials Properties

Material	Atom Density (cm ⁻³)	Melting Point (°C)	Thermal Conductivity (W/cm ² ° k)	Atom Ratio in Hydride	C _{max} (cm ⁻³)
Ti	5.7 x 10 ²²	1675	~ 0.114	~ 1.7	9.7 x 10 ²²
Y	3.0 x 10 ²²	1495	~ 0.15	~ 3.5	1 x 10 ²²
Zr	4.3 x 10 ²²	1852	~ 0.88	~ 1.9	8.2 x 10 ²²







